Laser Plasma Monochromatic Soft X-ray Source Using Nitrogen Gas Puff Target

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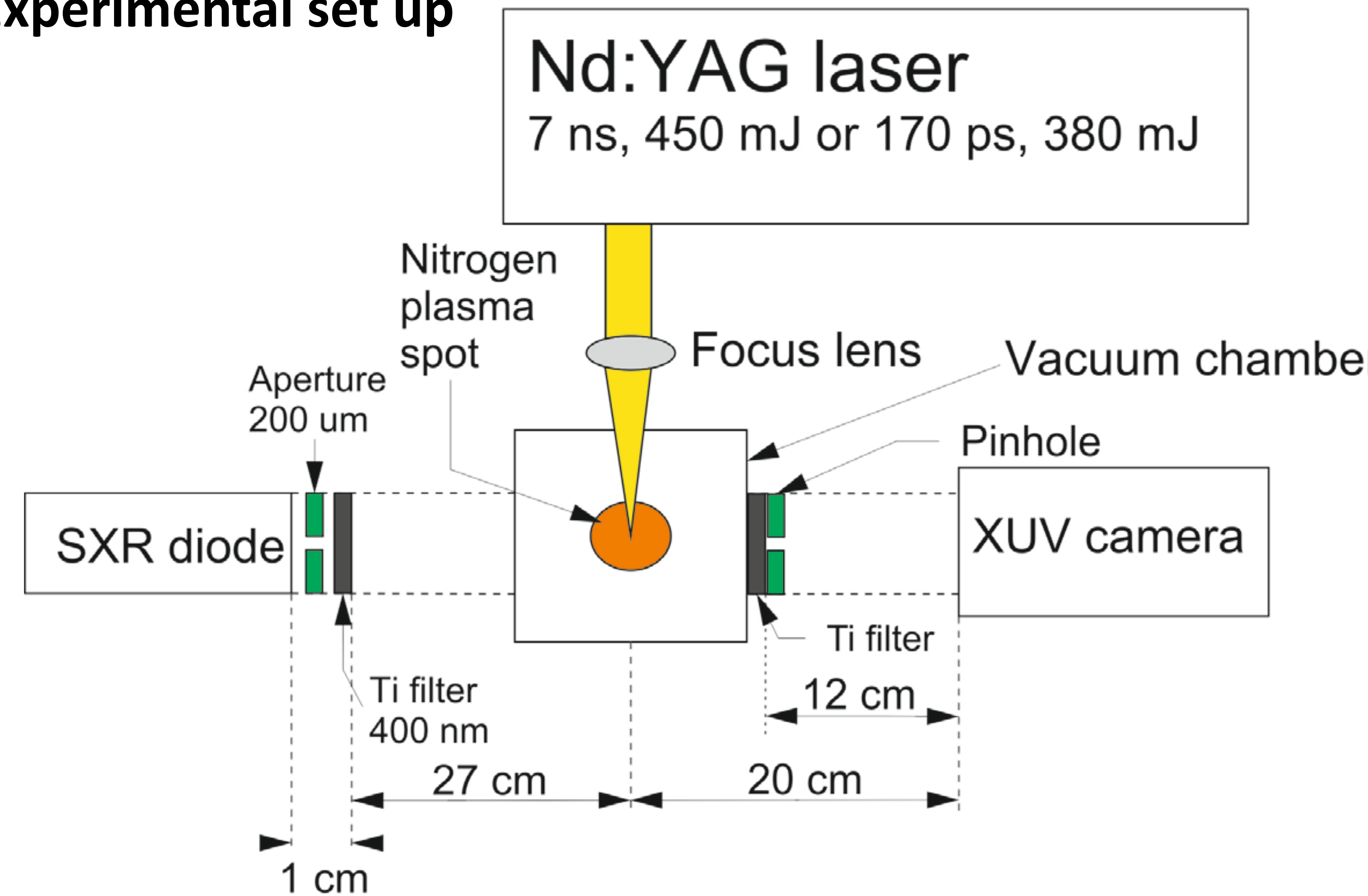
Outline

- Laser plasma created in nitrogen gas puff target is studied.
- Prevailing abundance of helium –like nitrogen ions is expected, if nitrogen plasma is heated up to temperature 40 ~ 80 eV.
- Monochromatic radiation with the wavelength λ = 2.88 nm, corresponding to the quantum transition $1s^2$-1s2p of helium like nitrogen ion, is expected.
- Laboratory experiments.
- Computer modeling.
- SXR emission of plasma heated by 7 ns and 170 ps Nd:YAG laser pulses is compared.
- Influence of laser pulse duration and energy and nitrogen gas density on the brightness of the SXR source is judged.

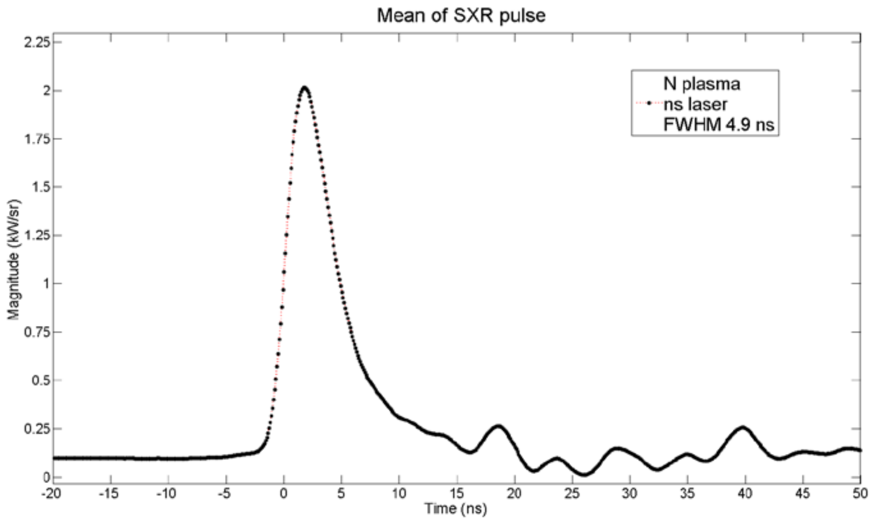
Experimental set up

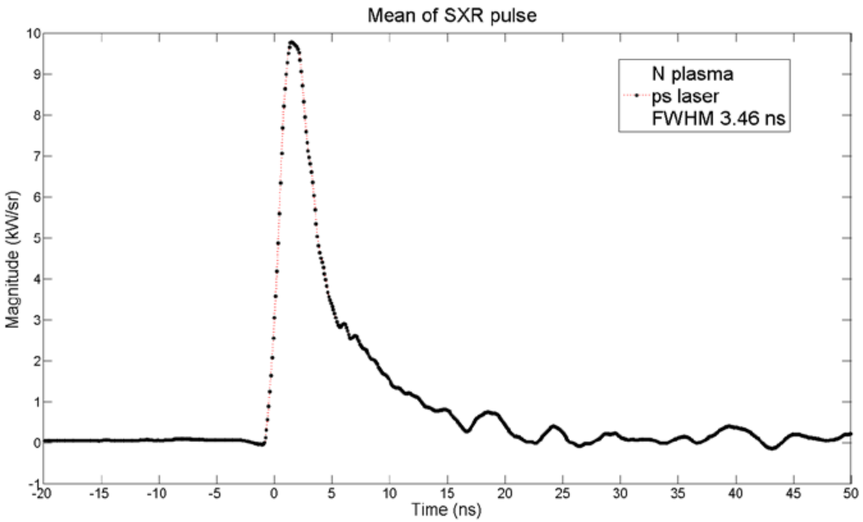


MÜLLER, M. et al.: Emission properties of ns and ps laser-induced soft x-ray sources using pulsed gas jets. Optics Express 2013, vol. 21, p. 12831

Emitted in-band SXR power

Input: **450 mJ/7 ns laser pulse** **380mJ/170 ps laser pulse**





Output: **0.12 mJ/4.9 ns SXR pulse** **0.43 mJ/3.5 ns SXR pulse**

Conversion efficiency: **2.7×10^{-2} %** **Conversion efficiency: 1.1×10^{-1} %**

Modeling by Z-star code

- 2D - RMHD code

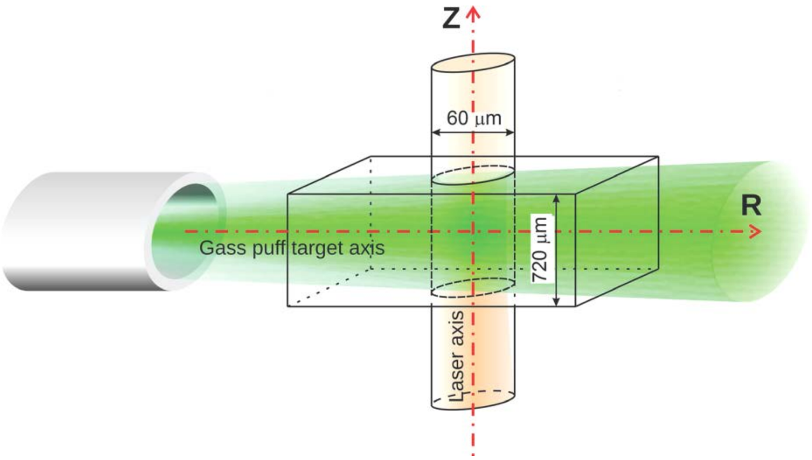
Presumptions

- Rotational symmetry
- Axis of symmetry coincides with laser beam axis .
- Z coordinate is oriented in the opposite direction to the laser beam propagation.
- Gas stream approximated by a gas layer

Evaluated space-time development

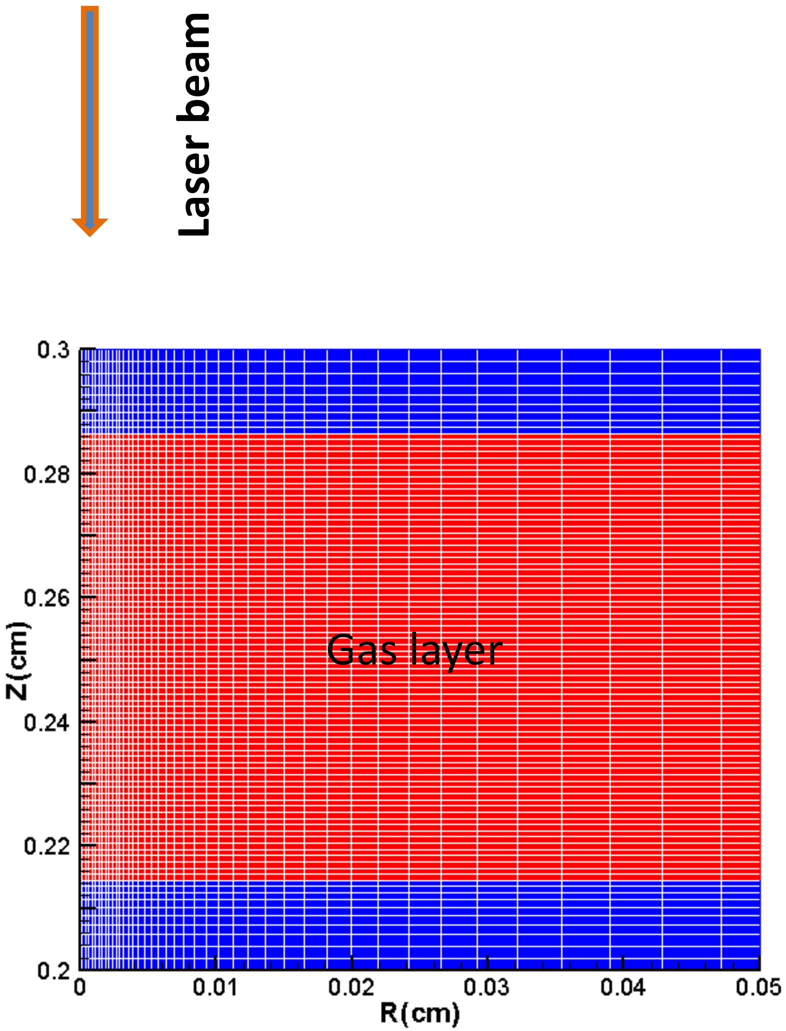
- Plasma parameters
- Radiation properties
- Emission in spectral band

  2.876 nm < λ < 2.886 nm



ZAKHAROV S.V. et. al.: in EUV Source for lithography, SPIE Press 2005, p. 223
VRBA P. et. al.: Physics of Plasmas 21 (2014) 073301-6

Z-star code – input parameters



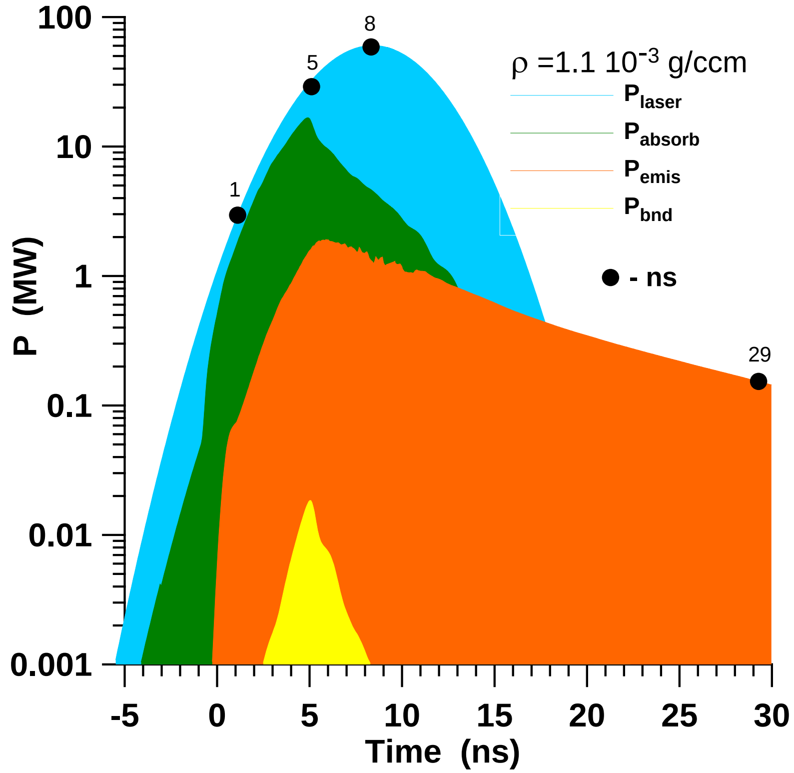
Laser parameters		
Laser energy [mJ]	450	380
Pulse duration [FWHM ns]	7	0.17
Peak power [W]	$6.4 \cdot 10^7$	$2.24 \cdot 10^9$
Focal spot radius [cm]	0.006	0.006
Focal position [cm]	0.25	0.25

Gas target parameters	
Thickness [mm]	0.72
Mass density [$g.cm^{-3}$]	$(3.7 - 31) \cdot 10^{-4}$

Absorbed and emitted power

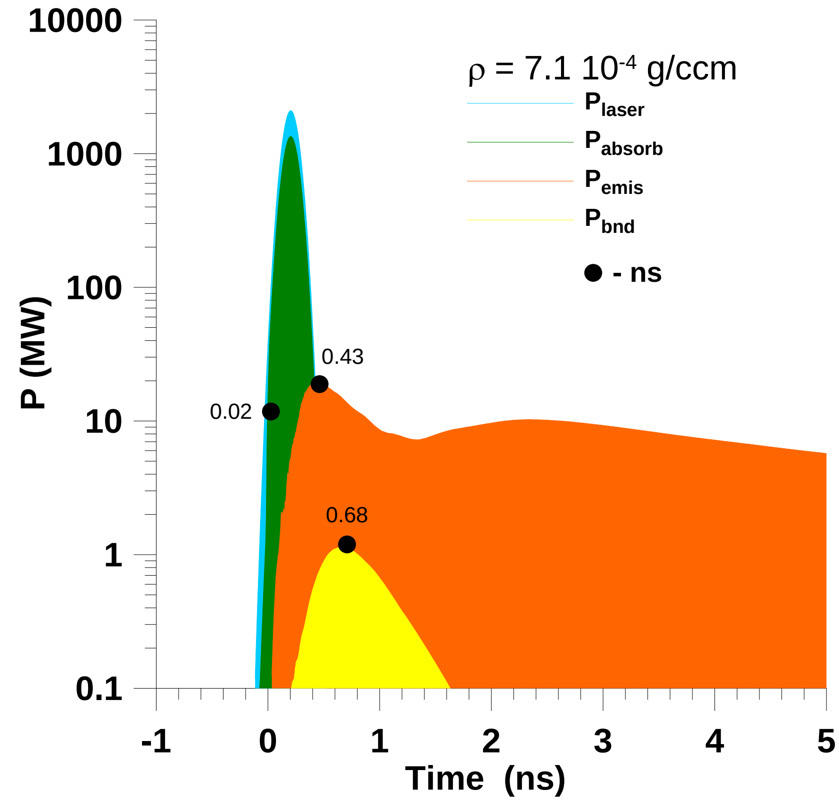
(results of simulations)

7 ns laser pulse



0.02 mJ/1ns SXR pulse

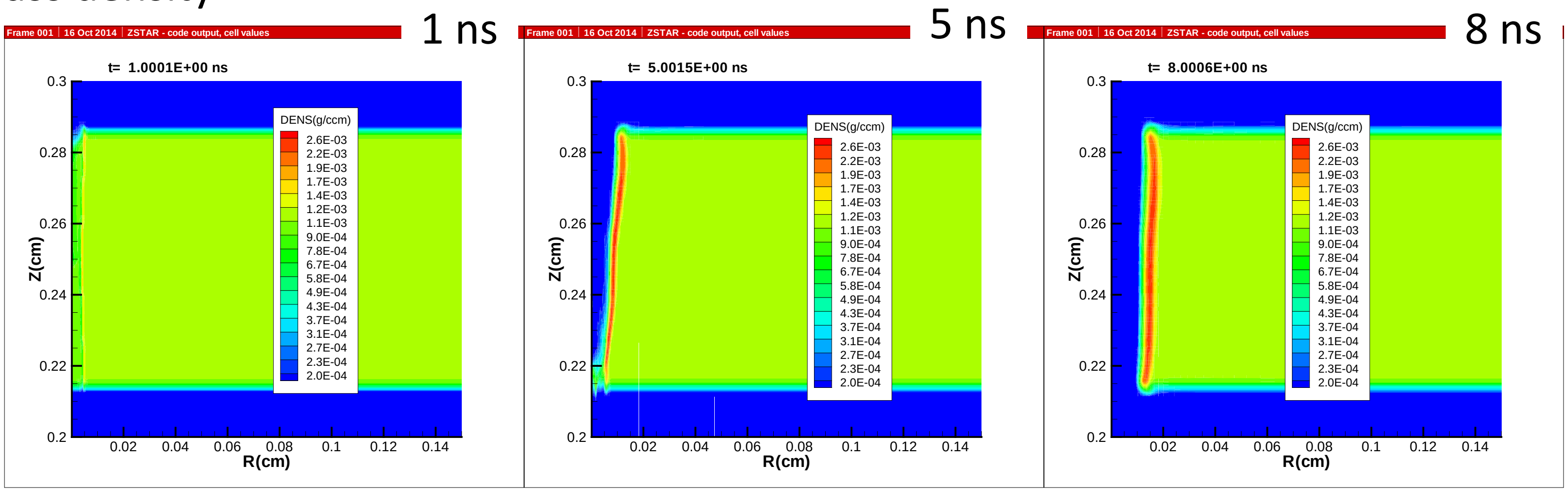
170 ps laser pulse



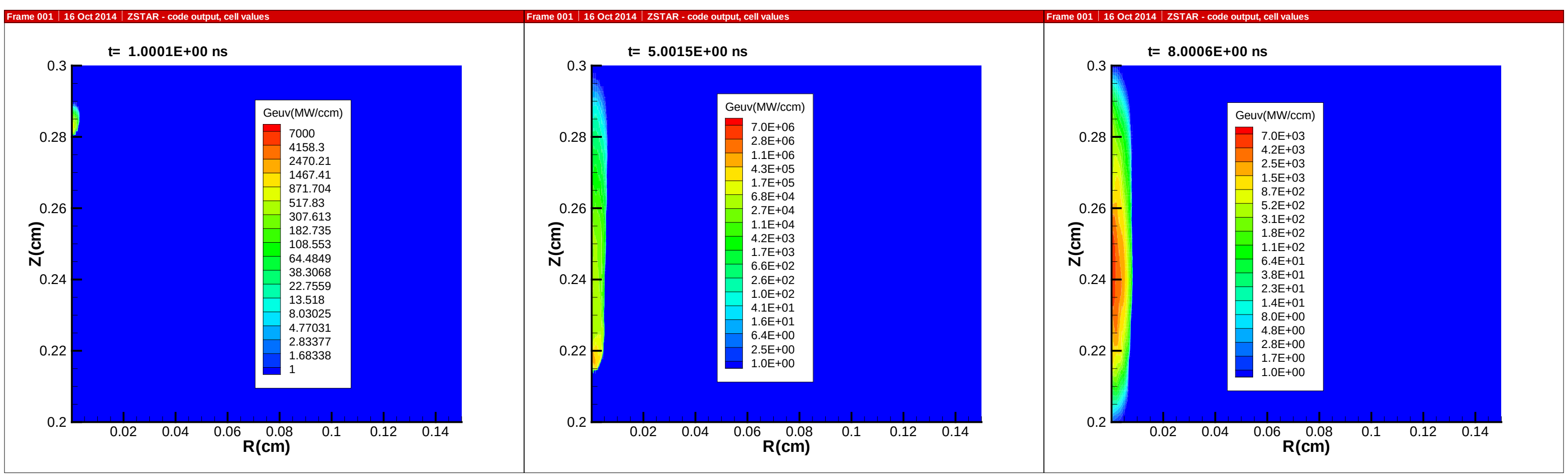
0.6 mJ/0.6 ns SXR pulse

Plasma spatial evolution – 7ns laser pulse

Mass density

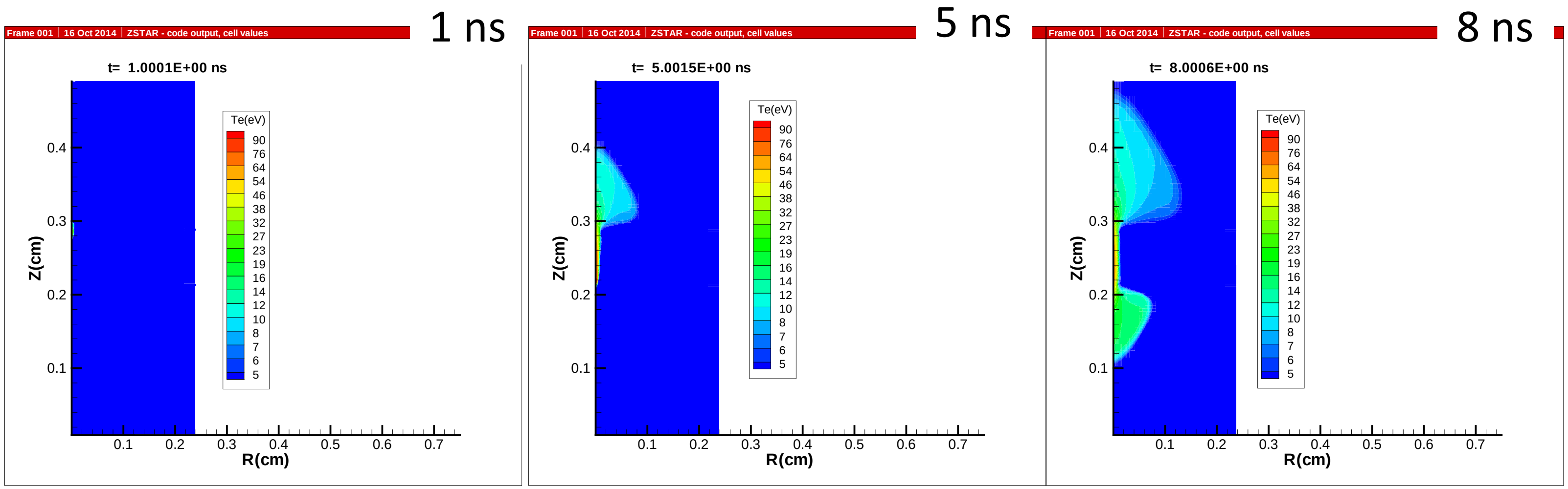


Emitted SXR power

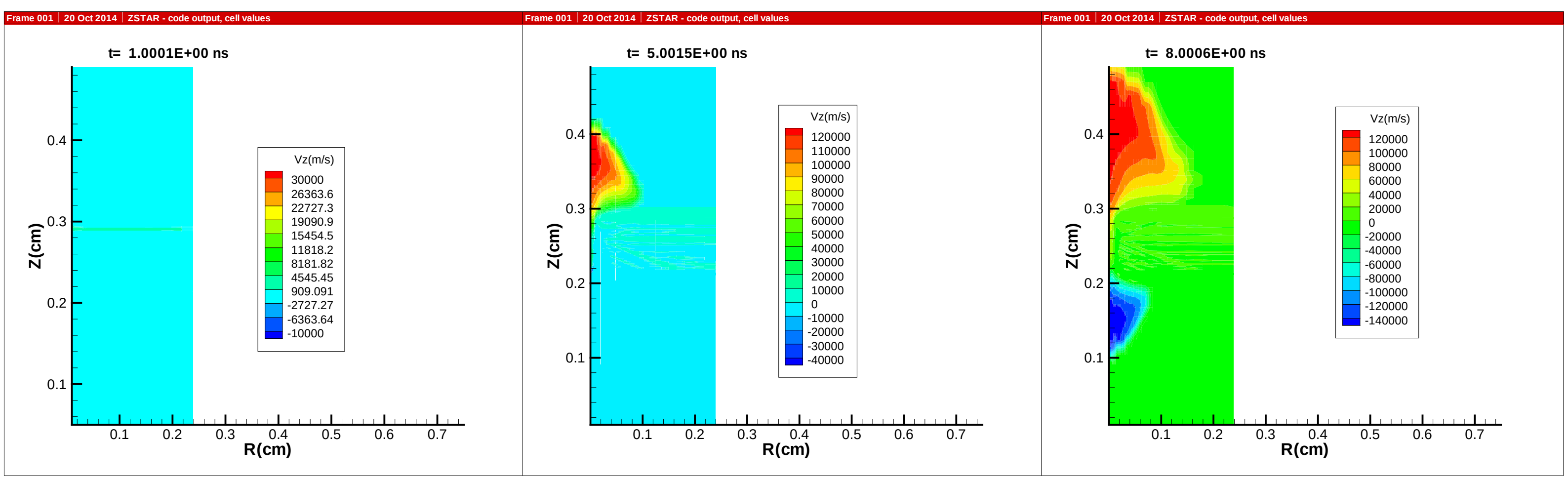


Plasma spatial evolution – 7ns laser pulse

Plasma electron temperature

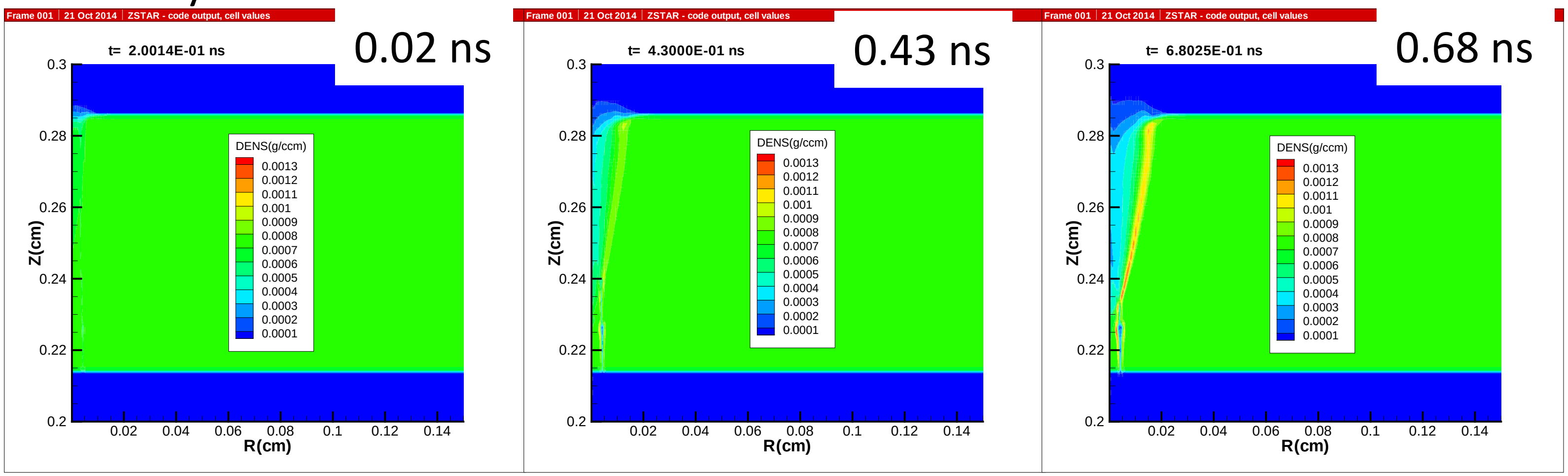


Longitudinal plasma velocity

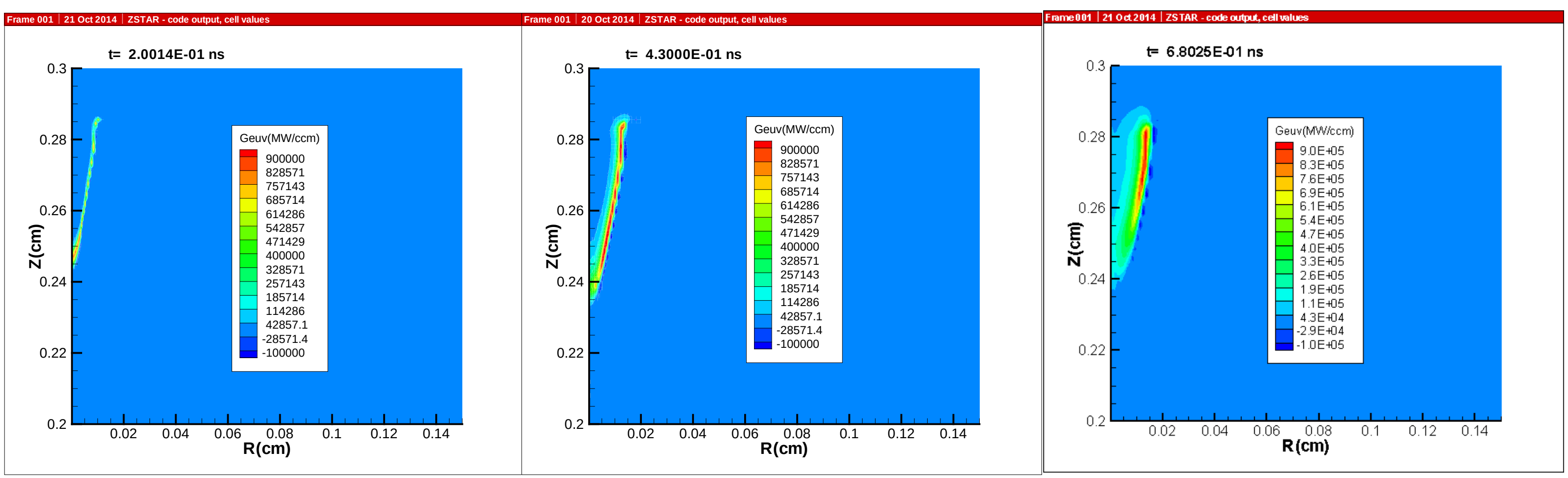


Plasma spatial evolution – 170 ps laser pulse

Mass density



Emitted SXR power

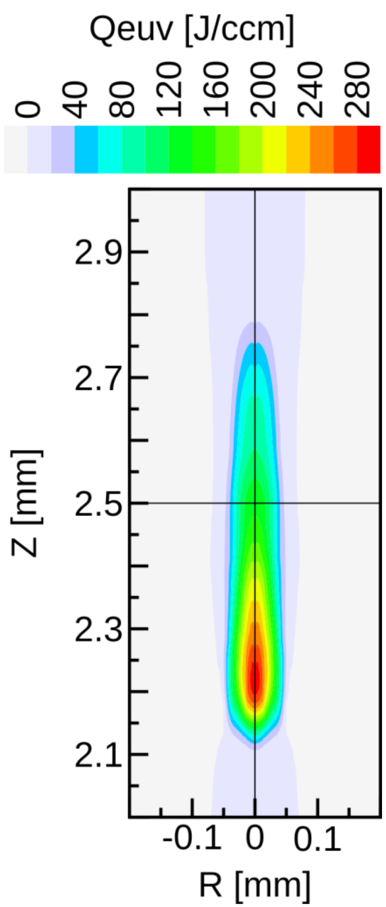


Spatial distribution of emitted SXR energy

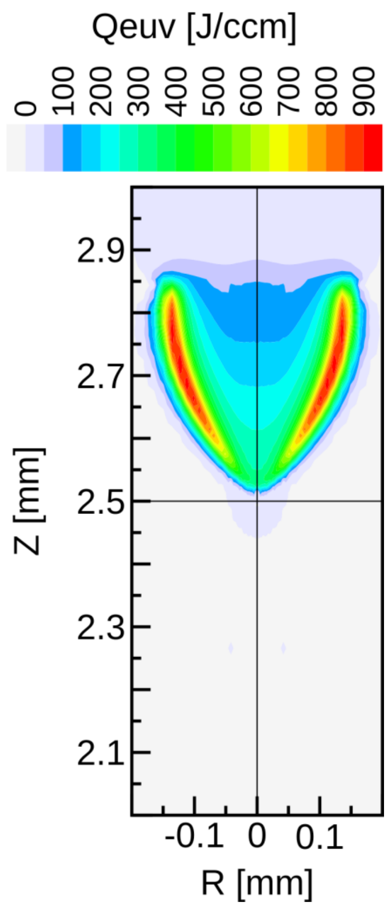
Simulations (Energy density)

Cross-section in R-Z coordinates

7 ns laser pulse



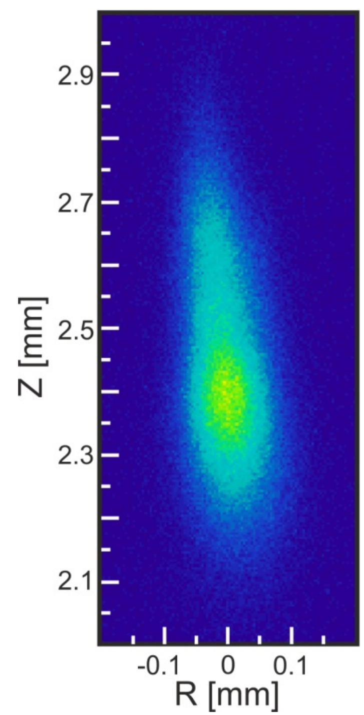
170 ps laser pulse



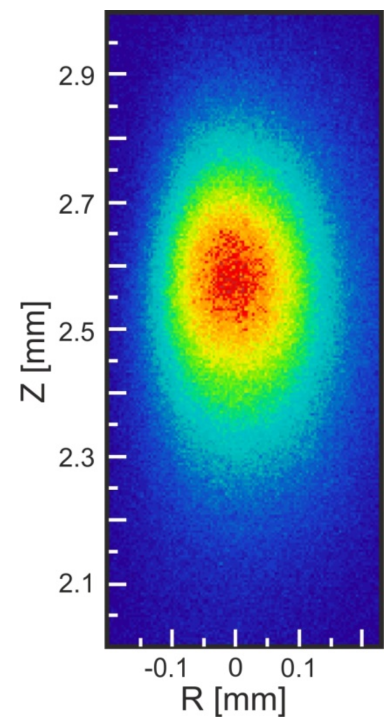
Observations

Pin-hole Imaging

7 ns laser pulse



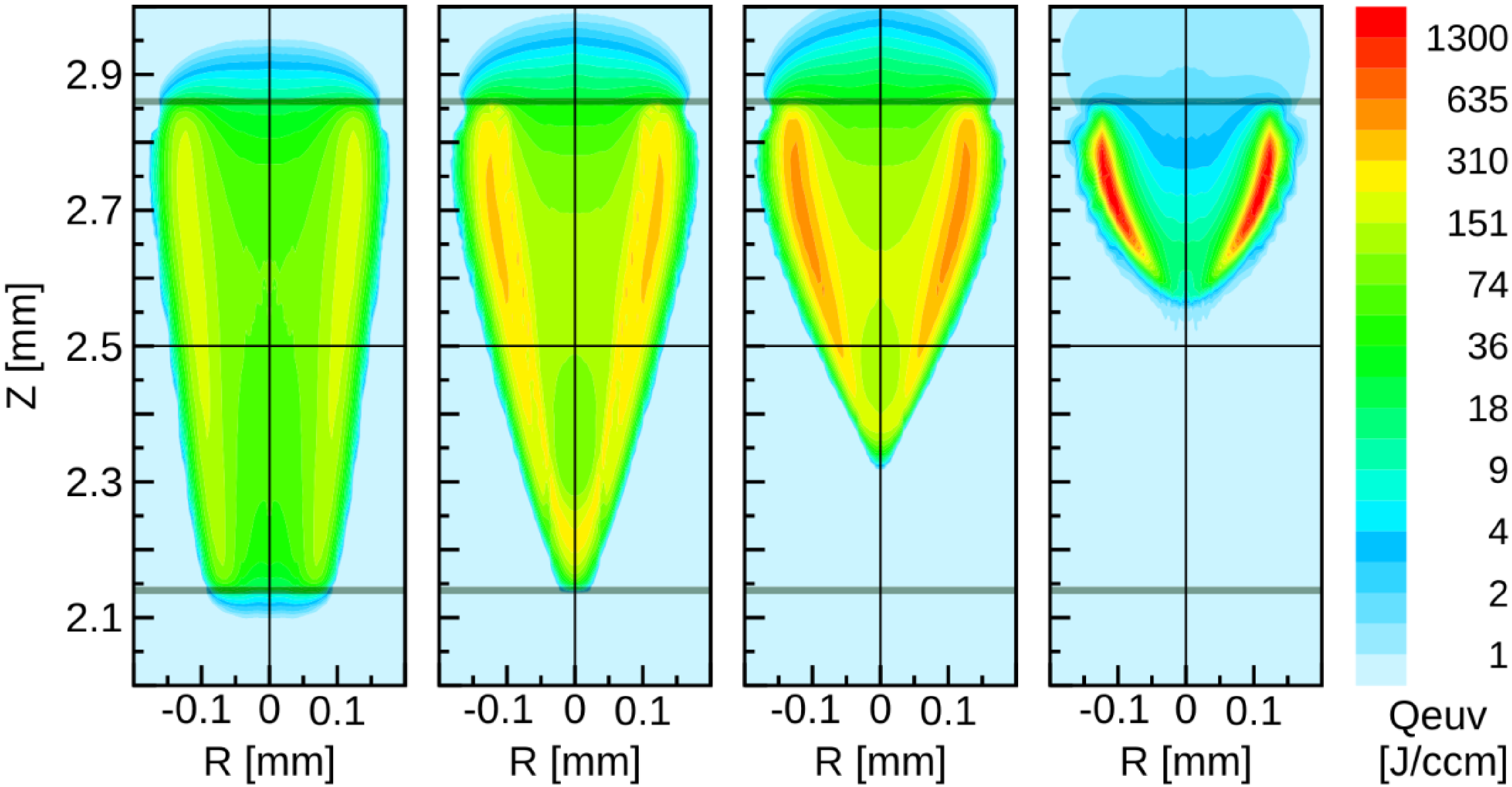
170 ps laser pulse



Spatial distribution of emitted SXR energy

(170 ps laser pulse and various target mass densities)

ρ = 3.7 10^{-4} g.cm^{-3} 5.4 10^{-4} g.cm^{-3} 7.1 10^{-4} g.cm^{-3} 10.6 10^{-4} g.cm^{-3}



SXR energy and brightness vs target density

7 ns laser pulse

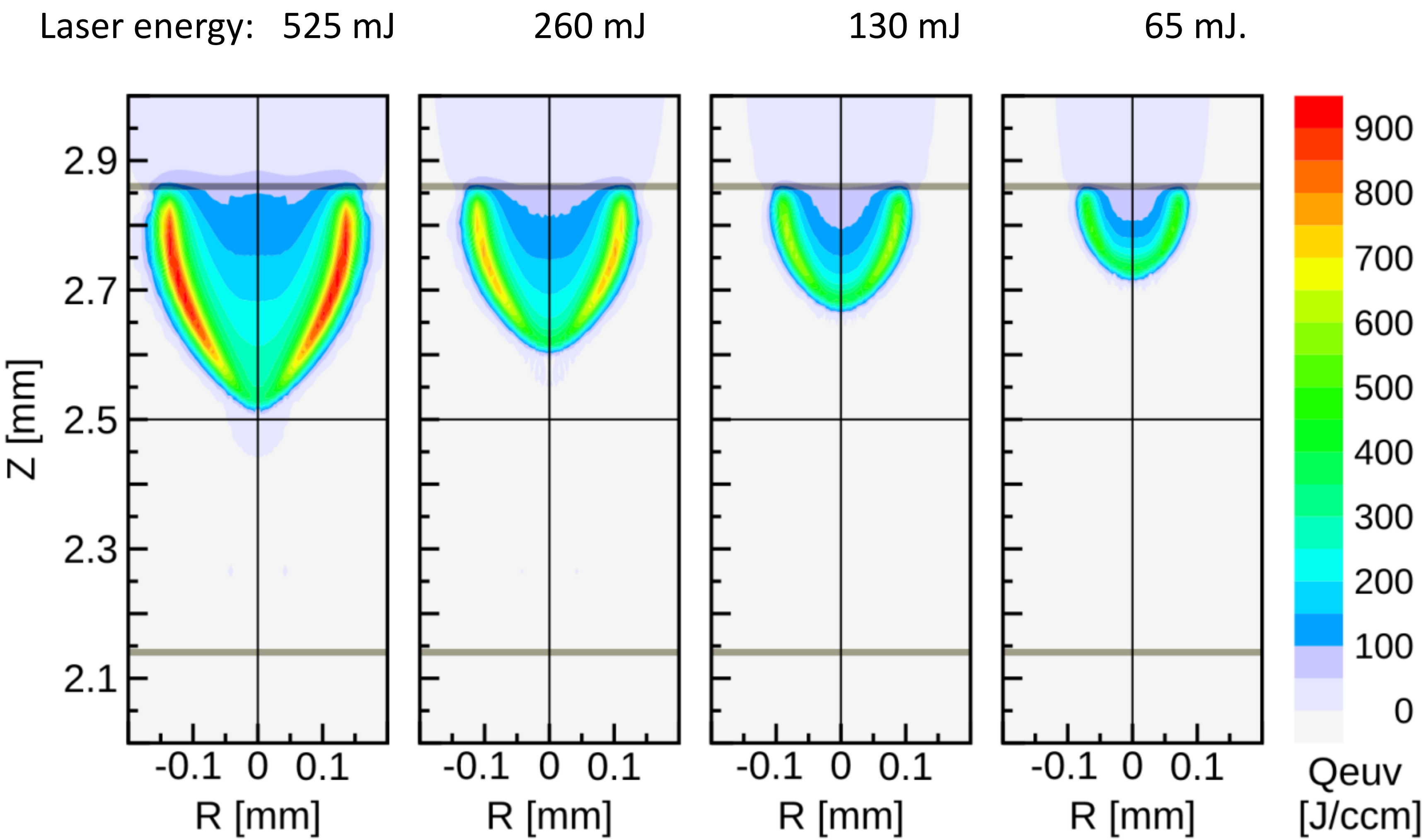
Mass density g.cm^{-3}	Spot imension ($2R_{spot}$ x Z_{spot}) μm^2	$Q_{euv,max}$ J.cm^{-3}	Energy in band mJ	Efficiency %	Brightness mJ.mm^{-2}.sr^{-1}
$3.7 \cdot 10^{-4}$	**60 x 660**	**1.57**	**0.000102**	**$2.26 \cdot 10^{-5}$**	**$2.26 \cdot 10^{-3}$**
$1.06 \cdot 10^{-3}$	**96 x 670**	**279**	**0.0365**	**$8.11 \cdot 10^{-3}$**	**$4.49 \cdot 10^{-2}$**
$3.1 \cdot 10^{-3}$	**132 x 780**	**1290**	**0.6543**	**$1.45 \cdot 10^{-1}$**	**$5.06 \cdot 10^{-1}$**

170 ps laser pulse

Mass density g.cm^{-3}	Spot dimension ($2R_{spot}$ x Z_{spot}) μm^2	$Q_{euv,max}$ J.cm^{-3}	Energy in band mJ	Efficiency %	Brightness mJ.mm^{-2}.sr^{-1}
$3.7 \cdot 10^{-4}$	**340 x 730**	**187**	**0.593**	**$1.559 \cdot 10^{-1}$**	**0.19**
$5.4 \cdot 10^{-4}$	**350 x 820**	**349**	**0.783**	**$2.059 \cdot 10^{-1}$**	**0.22**
$7.1 \cdot 10^{-4}$	**370 x 560**	**518**	**0.845**	**$2.223 \cdot 10^{-1}$**	**0.32**
$1.06 \cdot 10^{-3}$	**362 x 300**	**1337**	**0.854**	**$2.246 \cdot 10^{-1}$**	**0.63**

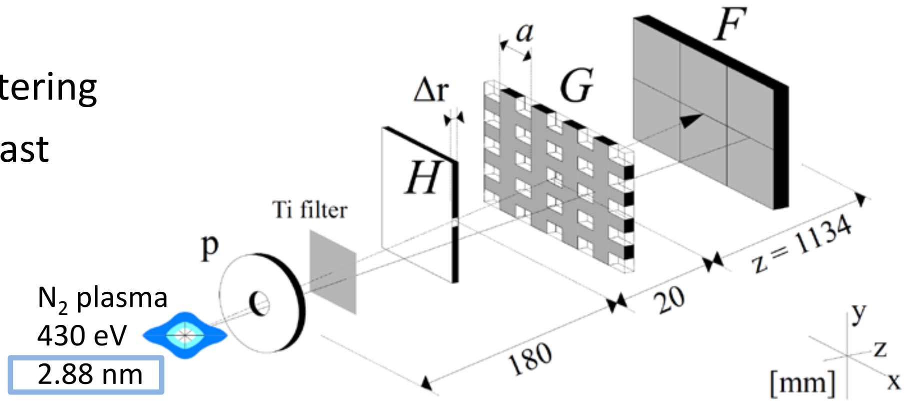
Spatial distribution of emitted SXR energy

for 170 ps laser pulse and various laser energies



SXR Spatial frequency heterodyne imaging (SFHI)

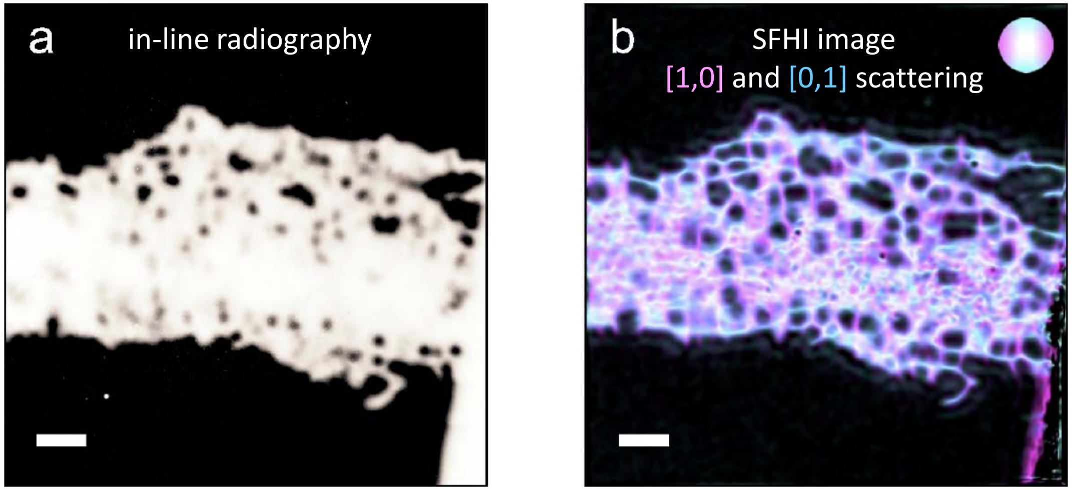
- inline X-ray imaging modality
  - attenuation
  - small-angle scattering
  - diff. phase contrast



- based on single transmission grating and Fourier analysis of image
- single-exposure

Demonstration of soft X-ray SFHI imaging on thin section of biological sample

5 µm section - *tendo calcaneus* of a Norway rat



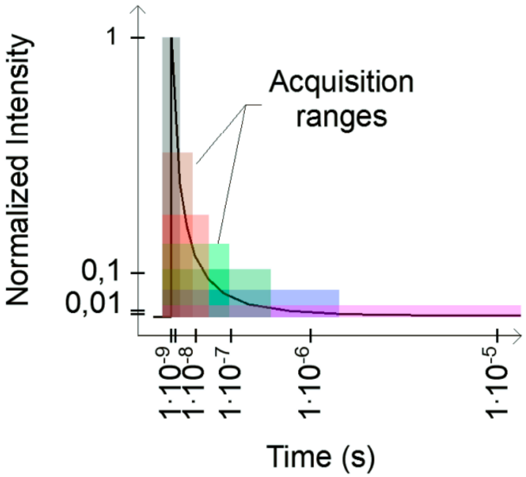
- ✓ additional information
- ✓ enhanced visibility
- ✓ negligible loss of spatial resolution
- ✓ SAXS anisotropy
- ✓ ad-hoc – no tedious alignment,
  – no modification of imaging setup

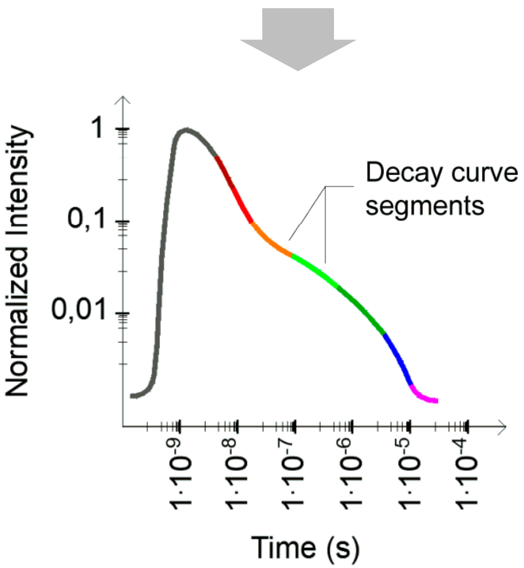
SXR time-resolved luminescence spectroscopy

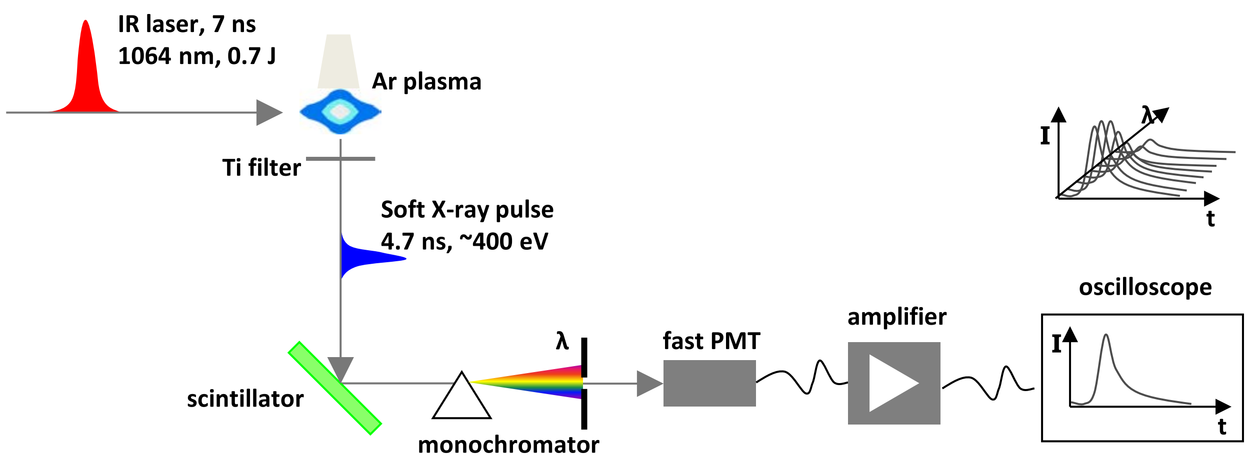
- Goals:
- to discover and assess defects in scintillation materials of biomedical importance
- to resolve the decay pathways (τ = ns .. ms) for better understanding of scintillation mechanism

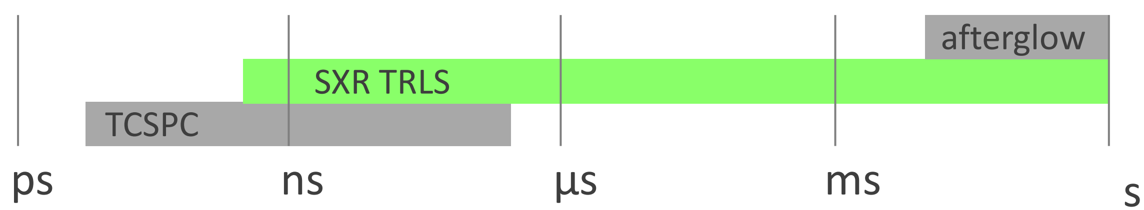
Outstanding sensitivity allow to distinguish both fast (ns) intense luminescence and slow (ms) weak one

Complementary method to TCSPC and afterglow measurement techniques









Conclusions

- Results of modeling correspond properly to the experiments:
  - In-band SXR emitted power (or energy),
  - Spatial distribution of in-band emitted energy (SXR source dimensions)
- Plasma induced by 7 ns laser pulse is created along the laser beam passing trough the gas stream. Laser pulse is not fully absorbed in the plasma.
  - If the mass density of the target is increased, the SXR emission becomes higher, the laser power is more absorbed by plasma.
- Plasma induced by 170 ps laser pulse is created around the border between gas and vacuum near the entry point of the laser beam.
  - The efficiency of in-band SXR generation is much higher with shorter pulse.
  - Further increase in mass density of nitrogen target has negligible effect.

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